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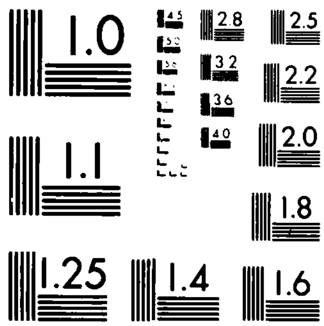

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COMPUTER AIDING OF MAINTAINABILITY DESIGN:

A FEASIBILITY STUDY

Douglas M. Towne
Mark C. Johnson

November 1984

Technical Report No. 104

BEHAVIORAL TECHNOLOGY LABORATORIES

Department of Psychology

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Computer-implemented processes have been developed to aid a designer in determining the maintainability consequences of design decisions. These processes operate upon detailed sequences of diagnosis and repair actions generated by a model of corrective maintenance performance, PROFILE.

The design aiding processes generate summaries of maintenance times, actions, false replacements, and other related maintenance measures to aid in the discovery of maintainability problems, the analysis of design options, and the projection of expected maintenance workload.

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With the completion of the fault simulation capability, the PROFILE model and its associated maintainability analysis processes can be employed within a conventional CAD environment.

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ACKNOWLEDGEMENTS

This research was sponsored by the Engineering Psychology Group, Office of Naval Research, Mr. Gerald S. Malecki serving as scientific officer. We wish to thank them for their support of this work.

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SECTION I. BACKGROUND

During the years 1980 to 1983 this organization developed, under Office of Naval Research sponsorship, a model of corrective maintenance performance which generates fault isolation and repair action sequences generally representative of those performed by trained technicians (Towne, Johnson, & Corwin, 1983).

The model, PROFILE, operates upon speci[illegible] [illegible] of the system design to generate representative sequences of mai[illegible]enance actions to diagnose and repair each of a sample of faults in a system. [illegible]FILE is a fully generic model of expert troubleshooting behavior, i.e., the intelligence to select and interpret tests is defined in a general manner, and is applied to any specific representation of a system. The specifications define the internal architecture of the system, the physical structure of the assembly, and the design of the external panels.

Other associated routines operate upon the generated action sequences to compute the manual times to perform each maintenance sequence. From this are produced distributions of repair times and relevant statistics such as Mean Time to Repair (MTTR) and maximum repair time.

Development of the Model

PROFILE is implemented as a computer program consisting of three primary operators: 1) a test selector, 2) a test performer, and 3) a test interpreter. These three program modules attempt to make testing decisions very much like those of expert maintenance technicians.

Given a sample fault, the test selector in PROFILE first determines the most effective test to perform to determine the status of major sub-systems. The test performer simulates the performance of the selected test by

obtaining, from a data base, the symptoms which the simulated fault would produce for that test. Then the test interpreter draws conclusions about the possible significance of the test result, in light of any previous results obtained.

A diagnosis sequence is generated for a sample fault by applying these three routines repeatedly until the true fault is identified and resolved.

The initial model of expert troubleshooting behavior attempted to minimize the time to accomplish corrective maintenance, without regard for the spare parts consummed. This model was exhaustively compared to detailed troubleshooting sequences of expert technicians, and was found to call for replacement when further testing would be more economical.

In this study, forty-eight Navy electronics instructors attempted to individually find and repair eight faults in a small computer system, including keyboard, disk drives, CRT, and printer. To achieve high control for this model-development phase, a computer was used to administer the problems. The participant selected tests at the computer keyboard, and then viewed a video tape segment of the test being performed, and results being obtained. Replacements were similarly requested at the keyboard, and presented by video tape segements.

The overly narrow objective of the initial model caused it to perform replacements of system modules when real technicians would ordinarily continue testing. After lengthy refinement and enhancement of the model, the present PROFILE model emerged. The model's replacement decisions are now shaped by parameters reflecting costs of spare parts, spares availability, and urgency of the repair setting.

Major revisions were also made in the way in which a particular system's fault effects were represented. Initially the domain data for a system reflected the particular symptoms produced by each possible fault.

This data form required a high degree of analysis by a human expert, and necessitated a very large data base for a system under study. Comparison of the PROFILE performances with the actual troubleshooting sequences revealed that the human experts were not able to employ the full power of this symptom data in interpreting symptom information. As a result, the actual diagnosis sequences were considerably longer than the PROFILE projections.

A number of alternative representation forms were then submitted to the model, to determine if the symptom data could somehow be obscured in a natural and systemmatic fashion, and more realistic diagnosis sequences obtained. A form was finally tested which yielded extremely realistic testing sequences. This data form reflects only cause-effect relationships such as

a fault in X MAY affect indicator Y
a fault in X WILL affect indicator Y
a fault in X CANNOT affect indicator Y

The successful use of this simpler fault effect data also allowed the domain-specific data for a particular system to be more compact and more easily prepared. In fact, as is discussed later, it is feasible to consider automated techniques for the generation of these data forms.

When changed as described above, the PROFILE model produced testing sequences whose times corresponded very closely with the means of the experimentally observed times, for each problem. Furthermore, the content of the generated testing sequences corresponded closely with that of the observed sequences.

As a validation, a second study was performed involving a different target system (an infrared transmitter/receiver) under two alternate designs. In this study the technicians performed tests on the transmitter/receiver until the fault was isolated and replaced. High correlations ($r=0.89$ for one design and $r=0.77$ for the second design) were obtained between the means of the observed times for the problems and the times projected by the model.

Objectives of the Feasibility Study

The PROFILE model has potential for addressing two general needs: 1) aiding the designer at the stage of product engineering when hardware packaging, layout, and human factors decisions are made, and 2) projecting the maintainability workload of a completed design proposal. Of these two possible applications, the former is considerably more challenging. Interacting with the designer in productive ways requires an involvement in the design process itself, whereas after-the-fact evaluation of a system design is essentially a subset of the larger design support requirement.

During the past year we have explored the feasibility of employing the PROFILE model as a design tool. The two central issues considered by this study have been 1) the types of design assistance which a PROFILE-based technique can make available to the designer, and 2) ways in which the required design specifications can most easily be acquired.

Design Assistance. *Section II will present the facilities which have* been developed to assist the designer in identifying and rectifying maintainability shortcomings in an emerging design. Operating upon the maintenance action projections of PROFILE, these functions offer the following:

* distributions of corrective maintenance times
* an analysis of the utilities of the maintenance-support features in the design for accomplishing fault diagnosis; these include such design features as front panel indicators, internal test points, and automated test features such as BIT and ATE.
* an analysis of false replacements
* a summary of the types and frequencies of maintenance actions required to resolve the sample of faults, and the proportion of time required to perform each type.

Facilitating Preparation of Design Data. Section III will describe the design of a simulation program which was formulated to effect substantial reductions in the skill and effort required to apply PROFILE to a design under development. The program has been designed to accept data of the type generally available from electronic CAD systems, paving the way for ultimate development of an integrated, computer-based system which offers maintainability design aiding within a conventional CAD-based design process.

Long-Term Objectives

Figure 1 illustrates the components of a complete system for computer-aided design for maintainability, which we term CAD-M, and the role of PROFILE in that total system. The heart of CAD-M lies in Block C, which contains PROFILE and the cognitive time model, and in block B, which contains the program for computing the time to accomplish a maintenance operation.

Block A contains the simulator designed during this study which accepts high-level inputs describing the functional architecture of the design and produces the fault-effects data shown in block B.

The routines which seek and display evidence of design weaknesses are shown in blocks D and E.

Also shown in these two blocks are 1) the true optimum fault diagnosis program (Towne, Johnson, & Corwin, 1982) which was developed using a dynamic programming formulation (in Block D), and 2) a routine which compares optimal maintenance performance to that projected by PROFILE (in Block E). If these are included in the total CAD-M system, the designer can be advised of the improvements which can result from aiding the maintainer's performance by providing online decision support. This decision support could be provided by a subset of the CAD-M software, specifically those functions involved in producing the optimum troubleshooting sequences.

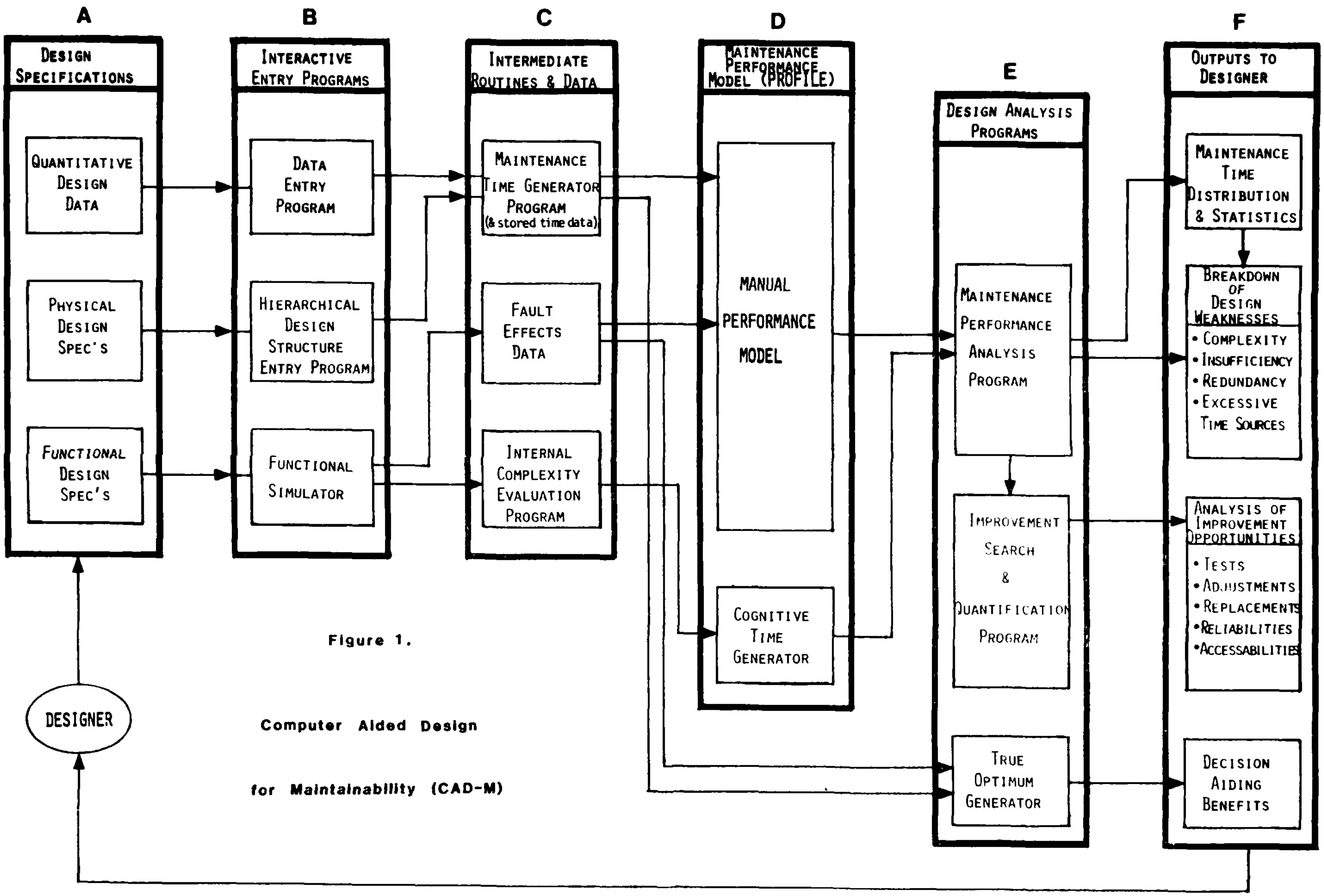

Figure 1.

Computer Aided Design

for Maintainability (CAD-M)

Current Status

The functions of CAD-M shown in blocks B through E are now complete except for the following:

* the Internal Complexity Evaluation Program (in block B)
* the Cognitive Time Generator (in block C)
* the Decision Aiding analysis (in block E)

The general design of a simulator to accept either CAD outputs or high-level design specifications from the designer is completed, and is described in Section III. This program will be implemented in the next year, along with the remaining input entry routines shown in block A of Figure 1.

SECTION II. INTELLIGENT AIDING OF DESIGN FOR MAINTAINABILITY

A computer-based maintainability design aid may ultimately operate in two different ways to support the consideration of maintainability issues during design. In the first mode, designers would apply the technique during the design cycle to analyze the maintainability implications of their decisions and approach. In the second possible mode of application, the technique might be applied over a longer term, to a range of design applications, in order to derive more general design principles which could guide designers in future efforts.

This section will deal primarily with the former application, but will conclude with a brief description of the types of general design relationships which might be derived from application in a research mode.

On-Line Aiding of Maintainability Design Decisions

A wide range of maintainability and human factors questions may arise concerning the attractiveness of alternatives during the design of a complex system. These questions might be classified into the following general categories:

Status:

How maintainable would the system be under the current design?

What maintenance actions would be involved in maintaining this system?

What consumption of spare parts is expected?

Change Evaluation:

How would the maintainability of the current design be affected by particular changes under consideration?

Simplification Analysis:

Can any of the maintenance features in the current system design be eliminated without impairing the maintainability of the system?

Critical Problem Identification:

Are there serious maintainability problems in the current design? What are they? How serious are they?

The following will describe data summaries produced by CAD-M to assist the designer in seeking answers to these four types of questions. The summaries are produced by programs which operate upon PROFILE-generated action sequences, for the sample of faults analyzed. To be meaningful, this sample must be constructed in a way which reflects the estimated failure probabilities of the system elements.

Status Summaries. The maintainability status of a current design is conveyed to the designer with three summaries:

a. a distribution of maintenance times (diagnosis plus repair), along with Mean Time to Repair and standard deviation, as shown in Figure 2. Currently, a single time distribution is produced, for the entire system. In the future, when systems are defined hierarchically, as described in section III, the time distributions and statistics will be obtainable for each unit in a system or sub-system. This will allow comparison, for example, of repair times for one circuit board to those of another board, or repairs of one module to another.

b. a summary of maintenance actions performed to resolve the faults analyzed by PROFILE, along with the time devoted to each action. An example of this work content summary is shown in Figure 3.

c. an analysis of replacements projected for the sample of faults analyzed, as shown in Figure 4. As opposed to a replacement projection based entirely upon reliability estimates, this summary also reflects the extent to which the system design promotes the incorrect, but not necessarily irrational, replacement of parts (as, for example, when a relatively inexpensive unit is provisionally replaced in preference to lengthy continued testing). Since the fault sample is based upon reliability data, the total replacement frequencies reflect both true failure likelihood and aspects of the design which promote false replacements.

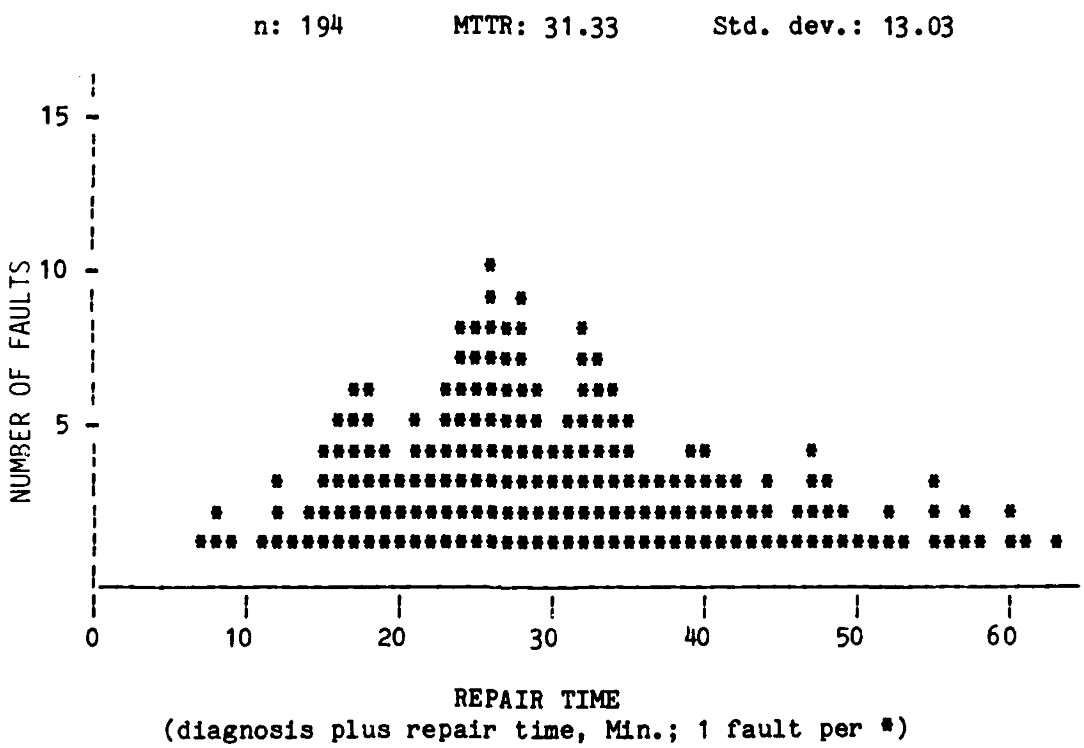

Figure 2. Example Repair Time Distribution

ACTION NAME	TO STATE	FREQ	TIME
POWER	ON	76	456
DTA-CBLE	IN	13	403
POWER	OFF	73	292
GROUND1	BRD3	25	210
CALIBRATE	YES	19	133
GROUND1	BRD2	17	100
SWEEP	10US	18	90
LEAD2	TP44	8	80
GROUND1	BRD1	9	70
MODE	DUAL	16	32
COUPLING	AC	10	20
MODE	SINGLE	9	18
VOLTS/DIV	50UV	2	10
CALIBRATE	NO	6	0

Figure 3. Work Content Summary

ID	REPLACEMENT	FREQ	RAWTIME	TOTAL
27	IC48 D FLIP	6	23	138
25	IC46 AND	6	23	138
24	IC45 AND	5	23	115
23	IC44 INVERT	5	23	115
17	PLL POT	12	8	96
36	CBL3	3	31	93
26	IC47 DIV16	4	23	92
14	IC33 PLL	3	23	69
20	IC41 DRIVER	3	23	69
10	IC31 OP AMP	3	23	69
7	IC21 PLL	3	23	69
32	XPWR	3	23	69
22	IC43 S/P	1	23	23

Figure 4. Replacement Analysis (including false replacements)

Change Evaluation. By evaluating the maintainability status before and after a contemplated change is specified to CAD-M, a designer can determine the projected impact of a wide range of design modifications. In this way the designer can explore the impact of such design decisions as modifications to the front panel, changes to the BIT or ATE systems, provision of test points, packaging of boards and modules, or selection of fasteners and means of accessing internal parts.

To measure the effect of a contemplated design change, a user would do the following:

1. execute CAD-M on the current design to obtain a measure of its maintainability status before the contemplated changes.

2. create a copy of the current design specifications and modify the copy to reflect the contemplated changes.

3. execute CAD-M on the modified design, and evaluate the differences.

4. if the designer chooses to implement the changes, the modified specifications become the current design; otherwise, the modified specifications are discarded.

Simplification Analysis. This category of maintainability analysis is concerned with identifying hardware included in a system design, strictly for maintainability purposes, which contributes very little to the serviceability. An indicator or test jack might turn out to be of no utility to the maintainer, or possibly some features of a built-in-test system might be unnecessary. Items found to be unused by CAD-M might be retained in a design for fulfilling other purposes; this analysis establishes a list of those elements which should be considered for elimination.

Unnecessary maintenance hardware is distinguished by a zero frequency of use in the CAD-M Test Usage Summary, Figure 5. In this example, all front panel indicators were used, but a number of test points were not.

ID	TEST	FREQ	X	TIME	=	TOTAL
15	TP 33	14		23		322
59	DELETE IR	15		19		285
25	TP 45, synch	6		33		198
23	TP 42	5		38		190
29	TP 49	5		38		190
1	Pwr on, observe disp	47		4		188
7	TP 6	4		38		152
26	TP 46	6		23		138
12	TP 24, Vcc Ir Xmit	10		12		120
14	TP 32	5		23		115
16	TP 34	5		23		115
13	TP 31	5		23		115
42	TP422	3		38		114
41	TP421	3		38		114
40	TP420	3		38		114
21	TP 39 Vcc IR Rec.	9		12		108
	•					
	•					
	•					
56	TP39X	0		12		0
5	TP 4, synch	0		33		0
57	GOLD IR	0		82		0
50	TP33X	0		23		0
32	TP412 synch	0		33		0
22	TP41	0		38		0
31	TP411	0		38		0
27	TP 47	0		38		0
28	TP 48	0		38		0

Figure 5. Test Usage Summary.

A second type of analysis, shown in Figure 6, displays the relative power of the fault diagnosis features of a design for identifying faults. In this analysis U-REDCT is the total uncertainty reduction contributed by each test, over the sample of faults analyzed. This is a measure of the extent to which the test aided in identifying the faults in the sample. The U/TIME column displays the fault isolation power divided by the time required to perform the test.

ID	TEST NAME	U-REDCT	U/TIME
59	DELETE IR	497.46	26.18
60	PLL lock check	129.58	64.79
47	TP24X	102.69	8.56
1	Pwr on, observe disp	22.71	5.68
23	TP 42	19.35	0.51
16	TP 34	16.02	0.70
14	TP 32	13.14	0.57
15	TP 33	10.64	0.46
19	TP 37	7.38	0.19
35	TP415	6.44	0.17
34	TP414	5.81	0.15
24	TP 44	3.40	0.09
25	TP 45, synch	3.40	0.10
36	TP416, Vcc Dig. Rec.	3.19	0.27
33	TP413	2.99	0.08
4	TP 3	2.47	0.11
52	TP35X	1.58	0.13
42	TP422	1.56	0.04
43	TP423, Vcc Dig. Disp	1.39	0.12
9	TP 21	0.79	0.02

Figure 6. Test Power Analysis

Critical Problem Identification. Critical maintainability problems would be evidenced by excessive repair times or excessive false replacements. The determination of just what repair time or false replacement rate is excessive is a subjective one, which the designer or logistics specialist must make. The identification of faults which are unusually difficult to resolve would begin by examining the maintenance time listing shown in Figure 7. Here the designer sees the total diagnosis and repair time projected for each fault in the sample. If some shared characteristics were noticed about many of the faults found to be difficult to resolve, the designer might request and examine detailed problem summaries, which provide the step-by-step sequence of projected testing actions for those faults.

ID	FAULT NAME	MEAN	STD	MIN	MAX
20	IC41 DRIVER	83.3	75.51	453	604
17	PLL POT	146.0	61.88	252	373
32	XPWR	156.3	21.39	263	305
14	IC33 PLL	281.7	49.43	406	503
10	IC31 OP AMP	305.0	76.79	39	172
7	IC21 PLL	410.3	59.01	431	544
27	IC48 D FLIP	449.0	15.82	139	170
25	IC46 AND	497.3	25.06	120	170
36	CBL3	529.3	56.09	346	449

Figure 7. Maintenance Time Listing

As shown in Figure 8, the detailed diagnosis and repair sequence lists the testing sequence projected for the fault with the times to perform the associated maintenance actions. From this, the designer may determine whether the repair time resulted from a difficulty in identifying the fault or from a difficulty in effecting the repair or adjustment, or both. In some cases, the analysis may show that a group of excess repair times is a result of mis-diagnosis which might be rectified by providing additional test points or displays.

```
******** New problem:  1 (ru = 36) ********


perform test   60  (PLL lock check)
          POWER:         ON  time = 6
            conditional time is    6,  combined total is   8
Observed symptom 0  (Normal)


perform test    1  (Pwr on, observe disp)
            conditional time is    0,  combined total is   4
Observed symptom 1  (Abnormal)


perform test   59  (DELETE IR)
          POWER:        OFF  time = 4
            conditional time is    4,  combined total is  23
Observed symptom 0  (Normal)
*critical*


perform test    1  (Pwr on, observe disp)
          POWER:         ON  time = 6
            conditional time is    6,  combined total is  10
Observed symptom 1  (Abnormal)
                  •
                  •
                  •


perform test   41  (TP421)
          POWER:         ON  time = 6
            conditional time is    0,  combined total is  38
Observed symptom 1  (Abnormal)


replace RU  36       CBL3              **REPLACMENT**
          POWER:        OFF  time = 4
            conditional time is    4,  combined total is  35


Fault resolved.  Total maint. time = 495
```

Figure 8. Detailed Diagnosis and Repair Sequence

Exploring Design Variables

The CAD-M technique has potential for exploring general principles of design for maintainability. Such principles could emerge as a result of long-term application to a range of design projects, or they may be the result of studies in which design variables are systematically manipulated. This section will briefly discuss some of the types of questions which may be addressed in this manner.

Test Power. A general question concerning the design of tests for fault diagnosis concerns the advisability of providing many relatively weak, but easily interpreted, tests versus fewer, more powerful, tests. There may be some range of test power which allows easy interpretation of symptoms, but which avoids excessive testing steps. A related question concerns the provision of test points versus front-panel indicators. Insights into the relative benefits of front panel indicators would be useful in determining when their added cost is warranted.

Level of Built-in Test. Experimentation with CAD-M may shed light on questions concerning the level of fault isolation which is most appropriate to address with BIT, as opposed to manual troubleshooting procedures. While generalities may be difficult to realize in this area, designers may obtain useful information regarding the times required in manual troubleshooting for various phases of diagnosis. Such data could be useful in determining the proper extent of a BIT capability.

Accessibility and Modularity. Designers often have considerable options concerning the packaging of hardware and the means by which sub-units are accessed. Typically, the designer can estimate the approximate cost difference among such alternatives, but has very little data on the maintainability consequences. For example, what is the payoff in mean repair time for each minute reduction in gaining access to internal test points? Or, how does Mean Time to Repair vary as the component count on circuit boards varies?

Other higher-level generalities may emerge which have implications in other aspects of equipment availability. One productive line of inquiry would be to investigate the sensitivity of repair times to the efficiency of the diagnostic strategy, and to the correctness of the symptom interpretations. Our tentative finding, based upon just three applications of CAD-M, is that repair times are not highly sensitive to efficiency, but are highly affected by symptom interpretation accuracy. If this tentative finding holds up to thorough experimentation, it would have implications for both designers and trainers.

A second attitude which we are coming to embrace as a result of applying CAD-M is that the design of equipment may be responsible for many more false replacements than is currently recognized. This suspicion is a result of observing a substantial false replacement rate when CAD-M applies an entirely rational diagnostic strategy to some designs. The general opinion in the maintenance world seems to be that false replacements are almost entirely the result of poor technician ability or training.

SECTION III. TECHNIQUES FOR SPECIFYING SYSTEM DESIGNS

The input data required to execute the PROFILE model constitute a well-defined specification of the information which must be supplied to support analysis of maintainability. In the experimental applications to date, the required alphanumeric data have been prepared to describe a particular system design, and have been entered via keyboard in the form shown in Appendix A.

The two major portions of the current specification format are: 1) the fault-effects array, which relates possible failures to their symptoms, and 2) the listing of symptoms for the specific faults comprising the sample to be analyzed.

Limitations of Manual Techniques

Unfortunately, considerable expertise and effort are required to formulate and enter these two data sets. Both can become voluminous and complex for a large system, and they may require an analysis of fault effects more extensive than that required to accomplish the functional design of the system. This could present a serious obstacle to effective application of CAD-M, as organizations may not be inclined to expend the resources required to meet non-operational objectives.

Automating the Generation of Specification Data

A central consideration of this study has been the feasibility of generating the required fault-effect data from more easily produced system descriptions. Specifically, we have explored the means by which the data might be produced by a computer-based simulator operating upon graphic representations of the system's functional structure and organization.

This section will describe the necessary inputs to the simulator and briefly outline how it will generate the necessary data for PROFILE.

The primary functions of the program are to select and simulate faults in the representation of the system design. In this way it discovers and stores the effects of all possible 'element failures' in the system, i.e., all possible failures within hardware elements which cause one or more of their outputs to be abnormal. This class of failures can include breaks in signal lines, but it does not include failures which alter the structure of the system, i. e., two or more signal lines becoming incorrectly connected (short-circuits). Such failure effects could be obtained by altering the connectivity data, described below, to reflect the altered system structure, but this would require involvement by the user.

The simulator will initiate the analysis of a selected failure by determining how the failed element will behave in the selected failure mode. It will then trace the effects of the abnormal outputs throughout the system. The tracing of effects involves recognizing the connectivity of system elements, to determine the path of effects, and it involves simulation of the other system elements, to compute how they will react to abnormal inputs. Finally, the simulator will determine what symptoms will appear to the maintainer under various testing conditions. From this, it will construct the required fault-effects matrix and the sample of specific faults, in the form shown in Appendix A.

The Specification Technique

The three primary elements of data required to specify the functional organization of a system design will be as follows:

1. a definition of each 'basic' element in the system.
2. data describing the system connectivity, i.e., the routing of element outputs to other elements.
3. a definition of the functional hierarchy of the system.

Other data representing the physical construction of the system remain as described in earlier reports. These data include the reliabilities of the basic system elements, the approximate costs of the replaceable units, and the physical structure of the system.

Basic Element Definitions. A basic element is, by definition, a level of system organization which is not further defined in terms of a more detailed network description. Thus basic elements compose the lowest level of system description.

The definition of each basic element will include its name, names of its inputs and outputs, and a rule describing its possible faulty behaviors, as described below.

The user will decide which elements in a system shall be regarded as 'basic'. These will be elements whose behavior is relatively simple and whose internal structure is not a consideration of the designer (or is not yet a consideration of the designer). This freedom to establish the basic building blocks of a system design at any level can be exploited to reduce the quantity of detail supplied, thereby facilitating analysis of designs long before the details have been worked out.

Basic elements might be individual components, or possibly standard circuits or subassemblies which are employed without modification. For example, a complete power supply might be regarded as a basic element if its behavior is relatively simple (such as any failure causes an abnormal output), and the designer is not concerned with its internal makeup.

Generally, a complicated element with many outputs and failure modes would be described as a network of basic elements or other networks, rather than as a basic element. In this way, very complex systems, and resulting complex behavior, can be represented via a network of simpler elements.

The complexity of an element's behavior is reflected by the type of rule required to specify its possible modes of failure. Two standard rules of failure behavior will be built in, and can be selected by the user to describe any basic element. The first rule states that any failure of the element causes <u>all of its outputs</u> to be abnormal. The second built-in rule states that <u>each one</u> of the outputs can be abnormal, with an equal probability.

For analyses of preliminary designs, the CAD-M user may select either of these rules to apply to all basic elements, thereby avoiding this aspect of the specification altogether. Alternatively, either of the basic rules may be selected for each element. In the most complex case, when maximum accuracy is desired, the CAD-M user may define a unique rule for any element, which states just what combination of outputs can be abnormal, and the approximate probability of those combinations.

<u>System Connectivity</u>. The inputs and outputs defined for each basic element provide the connectivity information required to trace failures to their effects. These data reflect what inputs enter the system from the outside world, how these inputs pass through the system, and what outputs are measurable at test points or front panel indicators.

<u>Functional Hierarchy</u>. The functional hierarchy of a system specifies how basic elements are combined to form higher level functional units, how these are combined at higher levels, and so on. Ultimately, the total system may be represented as a configuration of a relatively small number of lower-level networks.

The role of the functional hierarchy is to partially compartmentalize information for PROFILE so that, at any stage in its fault diagnosis, it 1) restricts its search for faults to the current element under consideration, and 2) it encounters incomplete information about the behavior of an element

which either must be resolved by exploring the sub-structure of the element or must be endured by limiting the power of the conclusions drawn from test results.

When a system is specified as a hierarchical structure of basic elements, very complex system behavior can be discovered by the simulator, as a result of analyzing the propagation of fault effects through the functional units. This fault analysis may well be a product of value in its own right, as well as providing the necessary ingredients to PROFILE.

As a simple example of the inferencing of fault effects, Figure 9 shows a portion of a two-level hierarchy; the top-level system is labeled A, and one of its sub-elements, A.B, is shown in further detail. Assuming that all sub-elements of A.B are basic elements, and that they follow the simplest failure mode rule (any failure produces all abnormal outputs), the following inferences may be made about the effects of two particular failures:

Failure in A.B.A: The abnormal signals in A.B will be 9, 10, 11, 12, and 4. The abnormal signals in A will be 4, 5, 6, 7, and 8 (signal 4 in A is identical to signal 4 in A.B).

Failure in A.A: The abnormal signals in A will be 3, 5, 6, 4, 7, and 8. The abnormal signals in A.B will be 11 and 4.

This type of inferencing is the type which existing artificial intelligence systems, such as PROLOG (Clocksin & Mellish, 1981), can do. Our experimental applications of PROLOG have led us to conclude, however, that CAD-M requires a simulator developed specifically to analyze hierarchical structures such as that shown in Figure 9. The two primary advantages of developing such a capability will be much faster execution speed and a great reduction in the quantity of data required to represent a system. Both of these advantages will result from building processes into the simulator which would otherwise be represented as data to a highly general-purpose system such as PROLOG.

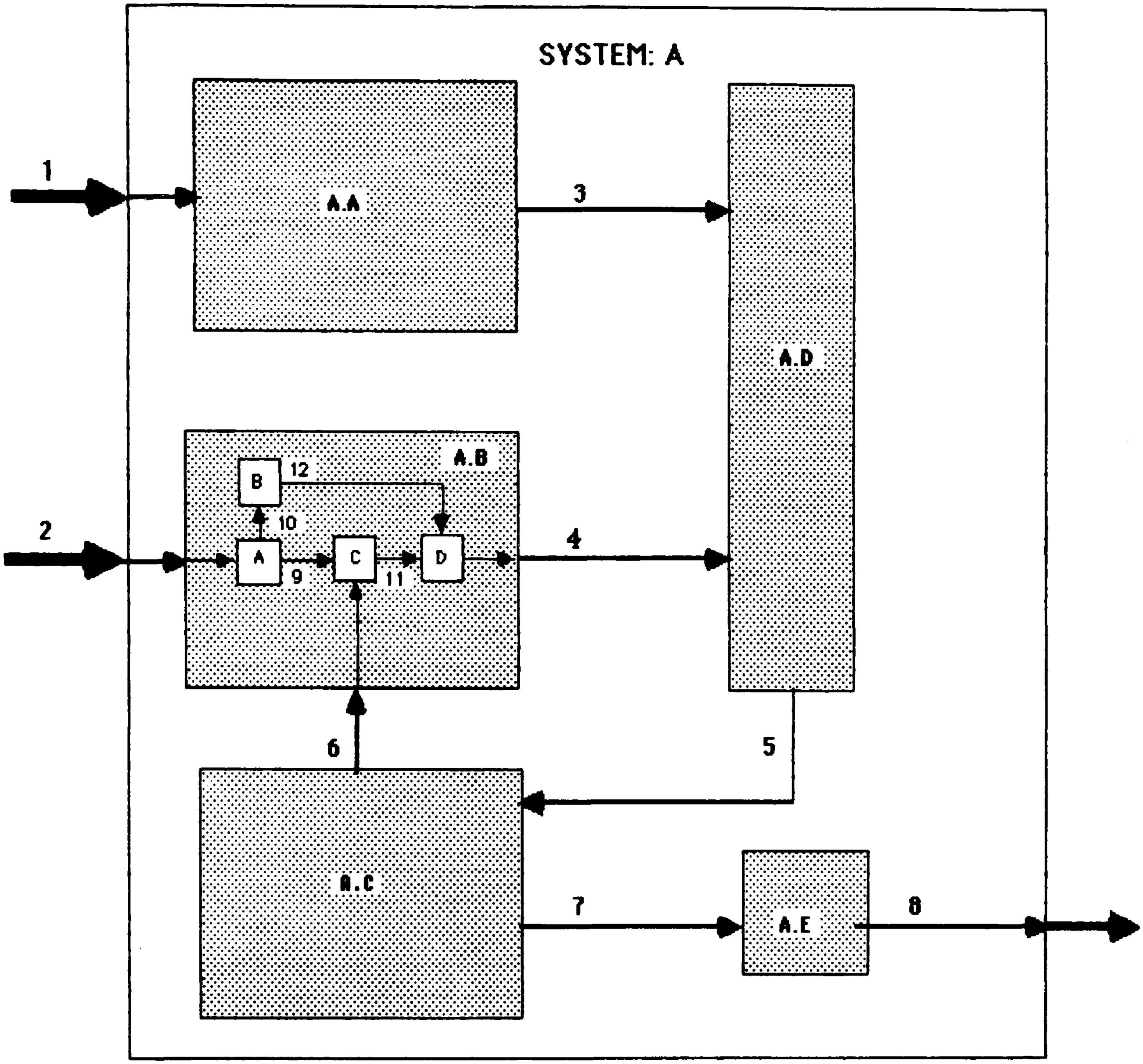

Figure 9. Example Functional Hierarchy.

One example of the type of mechanism which will be included in the simulator concerns multiple faults, or more specifically cascading faults (the causation of faults by other faults, as opposed to randomly occurring multiple faults). A simple input item could specify that a failure of some type in one element could cause a failure in another element. The simulator will process these simple entries, and will generate fault effect data which recognizes the probabilities of the cascading failure event. While the same operation could be generated in PROLOG, the data would have to supply PROLOG with all the mechanisms by which it generates the dependent failures and their effects.

Linking CAD-M to Existing CAD Systems

CAD systems for electronics design vary greatly, but in general they supply information concerning 1) the appearance of a physical system as a collection of lines or more complex graphical entities, 2) the electrical connectivity of points in circuits, in the form of wiring lists, and 3) some information concerning the sub-structures making up the system.

Sophisticated electronic CAD systems also have the capabilities to model the operation of low-level components, allowing a functional analysis of the operation of circuits and collections of circuits. Unfortunately, the simulation accomplished for design purposes differs in several important respects from the kind required to support the PROFILE model. Electronic CAD systems require data about components which is far more detailed than that required to support fault effect simulation. And, the specification of the system must be complete, at the very lowest levels, before modeling of circuit behavior can be initiated. As a result CAD is typically employed for the design of individual low-level circuits, rather than for simulating the high-level behavior of the complete system.

Furthermore, the types of results produced by electronic CAD systems are quite different than those required by PROFILE. The CAD results provide detailed timing diagrams, voltage levels, and other electronic characteristics, rather than the symptom information available at indicators and test points.

A final limitation of electronic CAD systems, for generating fault effect data for PROFILE, is that their application is restricted to electronic systems. A more generic resource would be preferred.

It is for these reasons that a general-purpose fault-effects simulator, as outlined above, is required within CAD-M.

The development of a simulator of this type will accomplish two major objectives: 1) it will facilitate the linking of CAD-M to commercial electronic CAD systems gaining wide use in industry, and 2) it will present a non-CAD user with a workable approach with which to supply design specifications.

Following development of this simulator, linking CAD-M to a particular conventional CAD system will require the development of a minimal, special-purpose interface between the CAD system and CAD-M. The particular transformations required will depend upon the CAD system involved; in most cases the extent of transformation is expected to be quite small.

Two types of interface are possible, 1) a 'pipe' through which are sent the data required by CAD-M, or 2) an online 'bus' by which CAD-M is able to receive data as it is developed on the CAD system. The former approach may be accomplished without requiring access to the inner structure of the CAD software; the latter approach would require involvement by the CAD developer. To establish clear interfacing specifications we will prepare a formal definition of the data requirements of CAD-M, along the philosophy of the Initial Graphics Exchange Specification (Smith, Bradford, & Wellington, 1983).

SECTION IV. SUMMARY AND CONCLUSIONS

Application of CAD-M

The CAD-M functions described in Section II have been developed to promote the discovery of maintainability problems, the analysis of design options, and the projection of expected maintenance workload. No assumptions have been made concerning exactly who in the design team might employ the process, when CAD-M might enter the design phase, or exactly how it would be applied. The intention has been to develop a system which does not require a highly structured application procedure.

A crucial underlying criterion, however, was that CAD-M address design issues which are largely under the control of the designer, and issues which are not deeply intertwined with achieving the intended operational requirements of the system under design.

In some development environments CAD-M might appropriately be integrated closely into a CAD system, providing maintainability analyses to the designer as the specifications are altered within the CAD system. In other settings, the technique might be applied as a discrete analysis phase, possibly by a team concentrating on logistics issues. In either case, an essential capability of CAD-M is that it will allow the analysis of preliminary design specifications when details are not yet established, and gradual refinement of maintainability projections as the details of the design evolve.

Future Research

The simulator described in Section III will be implemented in the coming year. Two alternate modes of data entry are planned, an alphanumeric mode and a graphical mode. The alphanumeric form will be developed first, and will accept input data which convey the functional topology of the system design. This mode of operation is important as it represents the most general interface between

PROFILE and existing CAD systems, i.e., the outputs of existing CAD systems are similar to the alphanumeric inputs required by the simulator.

The graphical input capability will be developed to facilitate use of CAD-M as a stand-alone, computer-aided system for maintainability design. The graphic editing features will be restricted to those required to specify the functional hierarchy, as described in Section III.

The final ingredient of CAD-M to be developed is a technique for projecting the cognitive time component of diagnose and repair operations. Preliminary regression studies indicate that acceptably accurate cognitive time estimates can be made using the manual testing projections of PROFILE as a basis. The key factors which have been identified as significant variables are (in order of decreasing significance) 1) the manual time projected by PROFILE to perform the fault-isolation tests, 2) the number of replacements made to resolve the failure, and 3) the number of unique indicators, including test points, examined to isolate the fault.

The precision with which cognitive time is predicted may be improved by adding some measure of system complexity. Previously, the data available to PROFILE have not reflected the functional complexity of the system. With the implementation of the hierarchical representation described in Section III, an opportunity will exist to examine the internal complexity of the system design. Such factors as linearity of system structure, multiplicity of failure modes, and predictability of fault effects may play an important role in projecting the cognitive workload associated with fault diagnosis. All of these will be measurable from the data structures to be employed in CAD-M.

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APPENDIX A FAULT EFFECTS DATA

1(IC11, P/S)	1	23	1	10000110177077701111011770777777777011177100000000000000
2(IC12, D FLIP)	1	23	1	10000010177077701111011770777777777011177100000000000000
3(IC15, D FLIP)	1	23	1	100011101770777011110111101111111110111111000000000000000
4(IC13 4060)	1	23	1	101111101770777011110111101111111110111111000000000000000
5(X11)	1	60	1	101111101770777011110111101111111110111111000000000000000
6(BCD SWITCH)	1	31	1	110001101770777011110110000000000000111001000000000000000
7(IC21 PLL)	1	23	1	1000000011011111111011110111111111101111110011011111111
8(D21 IR LED)	1	60	1	1000000000011111111011110111111111101111110000011111111
9(T21 2N222)	1	60	1	1000000000101111111011110111111111101111110001011111111
10(IC31 OP AMP)	1	23	1	1000000000000111111101111011111111110111111000000111111
11(IC34 OP AMP)	1	23	1	10000000000000001110111101111111111011111100000000000111
12(IC35 OP AMP)	1	23	1	10000000000000000110111101111111111011111100000000000011
13(IC32 INVERT)	1	23	1	1000000000000011111101111011111111110111111000000011111
14(IC33 PLL)	1	23	1	1000000000000011111011110111111111101111110000000011111
15(IC 36 NOR)	1	23	1	100000000000000000000000000000000000000000000000000000000
16(T31 PHOTO)	1	60	1	1000000000011111111011110111111111101111110000011111111
17*(PLL POT)	1	8	0	1000000000000011111011110111111111101111110000000011111
18(D31 DIODE)	1	60	1	1000000000000000000001111010000000000000000000000000000000
19(D32 LED)	1	60	1	1000000000000000000001111010000000000000000000000000000000
20(IC41 DRIVER)	1	23	1	200000000000000000000000000000000000010000000000000000000
21(IC42 DRIVER)	1	23	1	300000000000000000000000000000000000010000000000000000000
22(IC43 S/P)	1	23	1	800000000000000000000000000000000000011100000000000000000
23(IC44 INVERT)	1	23	1	10000000000000000000077707777777770111110000000000000000
24(IC45 AND)	1	23	1	10000000000000000000007701111111110111110000000000000000
25(IC46 AND)	1	23	1	10000000000000000000007707777777770111110000000000000000
26(IC47 DIV16)	1	23	1	10000000000000000000007707777777770111110000000000000000
27(IC48 D FLIP)	1	23	1	10000000000000000000000110111111111011111000000000000000
28(IC49 CLK)	1	23	1	10000000000000000000007711117777770111110000000000000000
29(X41 XTAL)	1	60	1	10000000000000000000007711117777770111110000000000000000
30(D41 MAN74A)	1	23	1	200000000000000000000000000000000000000000000000000000000
31(D42 MAN74A)	1	23	1	300000000000000000000000000000000000000000000000000000000
32(XPWR)	1	23	1	11111111111111111111011110111111111101111110111111111111
33(RPWR)	1	23	1	1000000000011111111111111111111111111111110000111111111
34(CBL1)	1	31	1	100000007117111111110111101111111111011111100000000000000
35(CBL2)	1	31	1	1000000000007777777771111011111111110111111000000000000000
36(CBL3)	1	31	1	10000000000000000000000000000000000001117777000000000000000
37(OPCL)	1	68	1	1000000000011111111011111111111111110111111000001111111

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